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Summary

According to the work program and schedule there was developed the methodology of experiments on the discharge chamber material influence on the Hall thruster characteristics, there was prepared Hall thruster model of the SPT-100 type for these experiments and there were manufactured the required discharge chamber parts (rings) made of the Russian BN-SiO₂ (borosil) ceramics and of the Russian AlN-BN (ABN) and Western ABN ceramics having secondary electron emission yield (SEY) different from that one for borosil. These parts were replaceable during experiments. Thruster model was equipped by set of the near wall probes mounted at external discharge chamber wall. There was made characterization of thruster model integral characteristics within the wide enough operation modes and the local plasma parameter distributions along its accelerating channel were determined under basic operation mode with discharge voltage 300V. As result of experiments there were found some differences in integral characteristics under some operations modes and in local plasma parameter distributions under the mentioned basic operation mode in spite of the fact that integral parameters under this basic operation mode were almost the same. Obtained data as a whole confirm that the discharge chamber wall properties have definite impact on the thruster operation.

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1. Introduction

As it is well known, the so-called Hall thrusters are used in the Russian space technology already many years and there is started their usage in the West. In this connection there is increased an interest of the western scientists and engineers to Hall thruster physics study and to development of new thrusters of this type. In particular there is great enough interest to the discharge chamber material property influence on thruster operation and performance /1-3/. Therefore under EOARD support there was initiated the study of the secondary electron-electron yield (SEEEY) of the typical ceramics used for the discharged chamber manufacturing and parallel theoretical /4/ and experimental studies of the Hall thruster operation and performance with discharge chamber made of the same ceramics /5/. It is supposed that complex of such parallel studies will allow to distinguish an influence of the ceramics properties on thruster operation physics and performance.

Investigation within this project is the continuation of the experimental study of the ceramics properties influence on thruster operation and performance made earlier /5/. The main goal of this investigation is to determine influence of ceramics on the local plasma parameter distribution inside the Hall thruster accelerating channel as well as on thruster integral parameters such as the discharge current and thrust under the same operation mode input parameters (discharge voltage and mass flow rate through the accelerating channel of thruster). To reach this goal there was prepared the Hall thruster laboratory model with set of electrostatic probes for the local plasma parameter determination inside the accelerating channel and with the exit part of the discharge chamber internal wall made as replaceable ring. There was manufactured several rings made of different ceramics having significantly different properties in comparison with the basic ceramics properties. It was assumed that comparison of integral and local plasma parameters inside the accelerating channel of thruster with the mentioned rings with different properties as well as the theoretical analysis of the mentioned difference impact made in parallel (out of frames of given project) will allow clarification of the discharge chamber wall properties impact on thruster operation and performance as well as obtaining of new data for analysis of this impact. Obtained results are summed in this report.

2. Technical description

As it was noted earlier /6/, one of the possibilities to realize the study of the discharge chamber material influence on thruster operation and performance is determination of thruster integral characteristics and local plasma parameter distributions inside its accelerating channel when the discharge chamber manufactured with replaceable ring made of ceramics with different properties and in particular made of ceramics with different secondary electron emission yield (SEY). And there was developed the methodology of experiments for such study during the 1st quarter /6/ including determination of thruster characteristics and local plasma parameter distributions under the same main parameters of the operation mode with discharge chamber having replaceable rings made of the Russian BN-SiO₂ ceramics (borosil) and AlN-BN (ABN) ceramics. It was supposed that there will be used the ABN(F) ceramics made in the West with known SEY to be delivered by AFRL. Due to delay with the mentioned delivery for the 1st experiments there was used also the ABN ceramics made in Russia.

So, to elaborate the mentioned methodology of study there was prepared thruster laboratory model with the replaceable rings made of borosil and ABN ceramics produced in Russia and there was made determination of integral characteristics of this thruster model (Fig.1, /6, 7/). This model besides traditional for SPT-100 four external coils and one internal (central) magnetization coil has one additional magnetization coil allowing more fine magnetic field topology optimization.

For these experiments there was prepared the test facility with vacuum chamber having internal diameter 2m and ~6m in length equipped by thrustmeter, system of the controllable anode and cathode gas feeding, power supply sources for all thruster circuits allowing obtaining of the discharge voltages till ~1kV. Integral characteristics were determined under variation of the mass flow rate through the accelerating channel within the range (2.5 – 4.5) mg/s and within the wide enough range of discharge voltages $U_d=200 - 700V$ with optimization of the magnetization currents in coils using the discharge current minimum criterion traditional for the Hall thrusters.

Obtained results /7/ had shown that prepared laboratory model has typical performance level for modern thrusters of the SPT-100 scale and there is observed relatively small (typically less than 5%) deviation of the discharge current (Fig.2), thrust (Fig.3) and thrust efficiency (Fig.4) under change of the ring material, but it is possible to distinguish this deviation under some operation modes. Taking this into account there was made preliminary determination of the local plasma parameter distributions along the external discharge chamber wall (Fig.5 - Fig.7) for the case of ring made of the borosil ceramics under basic operation mode. As such operation mode there was chosen that one with the mass flow rate 3.5mg/s and discharge voltage value ~300V. Choice of reduced mass flow rate relative to nominal one for SPT-100 is reasonable because it is planned within the next phase of work to study the local plasma parameters under operation modes with increased voltages. In this case the reduced mass flow rate allowing thruster operation with moderate discharge power under increased voltages is preferable (see Fig.8).

Obtained data (see Fig.5 - Fig.7) show that plasma parameter distributions have typical for SPT features /8/ and confirm the fact that laboratory model and probes design as well as the chosen operation mode are acceptable for further studies. Thus, it was decided that the methodology of study can be considered as elaborated one and during the 3rd quarter there was made measurement of the local plasma parameters with the ABN ceramics produced in Russia in order to get preliminary data on the influence of the ring material change on the local plasma parameter distributions /9/.

The mentioned measurement of the local plasma parameters with ring made of the Russian ABN ceramics were also made under basic operation mode with the mass flow rate through the accelerating channel ~3.5mg/s and discharge voltage value ~300V that is under the same main operation mode parameters as for the previous measurements for the borosil case /7/. As it was

mentioned above the difference of all integral parameters under optimized operation modes by minimization of the discharge current was relatively small (Table 1).

Table 1. Integral thruster parameters under basic operation mode with rings made of the BN-SiO₂ and ABN ceramics

Ring material	Discharge voltage, V	Mass flow rate, mg/s	Discharge current, A	Thrust, mN	Thrust efficiency
BN-SiO ₂	300	3.5	3.49	62.5	0.538
ABN	300	3.5	3.44	61.8	0.525

Measurement of the local plasma parameter distribution was made with usage of the same methodology as earlier and standard procedure of the probe characteristics processing. Obtained results /9/ for both ring materials (Fig.9 - Fig.14) had shown that the probe data indicate definite difference in the distributions along wall of the probe floating potential, electron temperature, electron current to the probe under plasma potential, plasma concentration (calculated using this current and electron temperature). At the same time distribution of the plasma potential and of the ion current to probe under its floating potential remain almost the same. So, change of the ring material has definite impact on the electron component parameters but does not change too much the ion flow dynamics and this could be a reason of the relatively small changes in integral thruster parameters under chosen basic operation mode. Unfortunately by now there is no data on the secondary electron emission of the ABN ceramics produced in Russia. Therefore it was interesting to study the influence of the Western ABN(F) ceramics produced by French MCSE company with more or less known secondary electron emission yield /5/. This study was done after receiving of such ceramics sample from AFRL. As earlier there was manufactured the replaceable ring made of this ceramics and there were determined integral thruster model characteristics (Fig.15 - Fig.19). Then, there were determined the plasma parameter distributions along the accelerating channel (Fig.20 - Fig.23).

Obtained results show that there is observed more significant difference in integral characteristics of thruster model with ring made of the Western ABN(F) ceramics in comparison with that one obtained for the Russian borosil and ABN ceramics and this difference is clearly observed under operation modes with increased discharge voltages. It is necessary to note also that the higher the mass flow rate and corresponding discharge current the lower the discharge voltage values where the mentioned difference becomes significant. This is an indication of the discharge chamber thermal state impact on thruster integral characteristics. It is necessary to add that such behavior of thruster integral characteristics is qualitatively similar to that one for small SPT with discharge chamber exit parts made of the same materials /5/. More over after several hours of thruster operation with ring made of ABN(F) under increased discharge voltages there were observed the breakdowns through the bulk of ring also similar to that ones observed with small SPT and creating holes in the bulk of rings /5/ and causing their cracking. In the given experiment the narrow slot was also observed in the case of ABN(F). Nevertheless the ring form and position was not changed and under basic operation mode all thruster parameters were still close to the initial ones and close to that ones for the borosil ring case (see data for ABN(F) (2) in Fig.15 – Fig.19). Therefore there were determined the local plasma parameter distributions with this ABN(F) ring under basic operation mode.

Results of the local plasma parameter distributions determination (Fig.20 - Fig.23) show that there are observed some significant differences of them for the ABN(F) ring in comparison with other cases especially in the ion current distributions along the accelerating channel (see Fig.23). One can see also that plasma potential near the external wall is higher than in other cases (see Fig.21). This is an indication of the fact that in spite of small changes in thruster output parameters

there is more significant change of its internal plasma parameter distributions than in the case of the Russian ABN. It is necessary to remind those thruster operation modes were optimized with usage of the discharge current minimum criterion. Therefore magnetic field topologies were not identical even under the same mass flow rate, discharge voltage and almost the same discharge current and thrust. This conclusion is confirmed by simulation of the magnetic field with amp-turns in the magnetization coils giving discharge current minimum for different ring materials under basic operation mode (Table 2, Fig.27 - Fig.29).

Table 2. Currents in the magnetization coils under optimized operation modes with the mass flow rate 3.5mg/s and discharge voltage ~300V

Ring material	Current in the central coil, A	Current in the external coils, A	Current in the 3 rd coil, A	Criterion of the operation mode optimization
Borosil	1.09	0.48	- 2.5	Discharge current minimum
ABN	1.21	0.49	- 2.5	Discharge current minimum
ABN(F)	0.93	1.09	- 2.58	Discharge current minimum

As one can see the magnetic field topology in the case of ABN(F) is significantly different from two other cases. If one takes into account that the electric field equipotential lines more or less follow the magnetic field lines /10/, one can derive from consideration of the magnetic field topologies that for the ABN(F) case (see Fig.26) the ion flow is to be shifted to the internal discharge chamber wall. Therefore it is understandable that the level of the ion currents to the probe at external wall in this case is lower than in other cases. Then, it is understandable also that under such magnetic field topology plasma potential near external wall is high enough (see Fig.21) what was also observed earlier /10/ while the accelerating layer was turned focusing ions to thruster axis.

As a whole obtained data show that the studied replacement of the ring material has definite impact on thruster operation and performance. But this impact is very complicated because in spite of the significant change of the local plasma parameter distributions the change of thruster integral parameters is relatively small at least under basic operation mode. It is necessary to add that this impact is to be more significant on thruster lifetime because the ion flow structure under optimized operation modes is changed significantly. Taking all the mentioned into account it seems reasonable to continue this study and preferable directions of the further studies are represented below.

3. Obtained results

Summarizing all represented above one can conclude that as results of activity within the project work program there were obtained the following:

- there was developed the methodology of study of the discharge chamber material influence on thruster operation and performance and there were prepared the test facility and Hall thruster laboratory model with set of the near wall probes mounted at the external wall of its discharge chamber and with replaceable ring made of the basic (borosil) and Russian AlN-BN (ABN) and Western ABN(F) ceramics to realize such study according to the developed methodology;

- there were determined the integral characteristics of the mentioned Hall thruster laboratory model with rings made of different materials and there was found difference in characteristics determined with different rings mostly notable in the case of the ABN(F) ceramics and in the case of increased discharge voltages while discharge current in this case was notably higher than that one for other cases;
- there were determined the local plasma parameter distributions along the accelerating channel of thruster model with different rings under the same main operation mode parameters (mass flow rate $\sim 3.5\text{mg/s}$, discharge voltage $\sim 300\text{V}$) and it was shown that replacement of the mentioned rings causes significant change of these distributions, namely:
 1. In the Russian ABN case all distributions are changed relative to that one for borosil case excluding the plasma potential and ion current distribution along wall.
 2. In the case of the ABN(F) ring the ion current distribution is changed significantly also. More over in this case the magnetic field topology optimized to get discharge current minimum is changed qualitatively causing shift of the ion flow to the internal wall. This effect has to cause reduction of the ion currents at external wall surface what is observed in experiment.
 3. As earlier there were observed the breakdowns through the bulk of ceramic ring in the case of the ABN(F) ceramics and ceramics bulk conductivity could be a reason of the increased discharge current and reduced thrust efficiency under increased discharge voltages in this case. Therefore application of the existing ABN(F) ceramics in the Hall thruster design is questionable.

As a whole one can note that there were obtained new data on the discharge chamber material influence on Hall thruster operation and performance. This influence is complicated enough and is to be studied more deeply theoretically and experimentally. In particular, obtained data could be used for more deep analysis of this influence by simulation of processes inside Hall thruster accelerating channel in the described experimental conditions taking into account difference of properties of the replaceable discharge chamber wall parts.

Concerning the further experimental activity it seems reasonable to realize similar study of local plasma parameter distributions under increased voltages with rings made of borosil and Russian ABN while energy of significant part of electrons can reach the level close to the threshold where the secondary electron emission yield is equal to 1 at least for one ceramics. In this case it is expected to observe more significant difference in operation thruster with rings made of different ceramics. And determinations of thruster integral characteristics within this project for the mentioned materials confirm this conclusion. It should be interesting also to determine the secondary electron emission characteristics for the Russian ABN ceramics.

4. Future work planned

It is planned that during phase 2 of this work there will be made the comparative study of integral characteristics and local plasma parameter distributions with rings made of the basic (borosil) and AlN-BN ceramics made in Russia under basic operation modes with the Xe mass flow rate through the accelerating channel $\sim 3.5\text{ mg/s}$ and with discharge voltage $U_d \sim 300\text{V} - 700\text{V}$ at least. As it was mentioned above one can expect the qualitatively new effects connected with fact that energy of the significant part of electrons can reach the secondary electron emission threshold. On base of these results it seems possible to derive more definite conclusion on the secondary electron emission role in Hall thruster operation.

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Appendix 1.

Figures

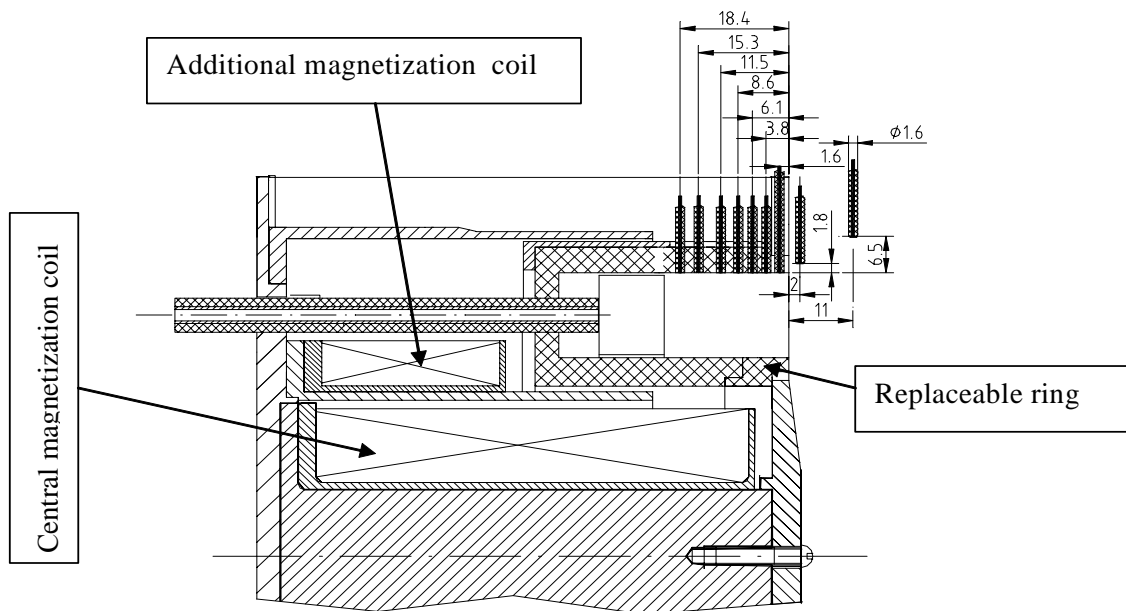


Fig. 1. Thruster laboratory model.

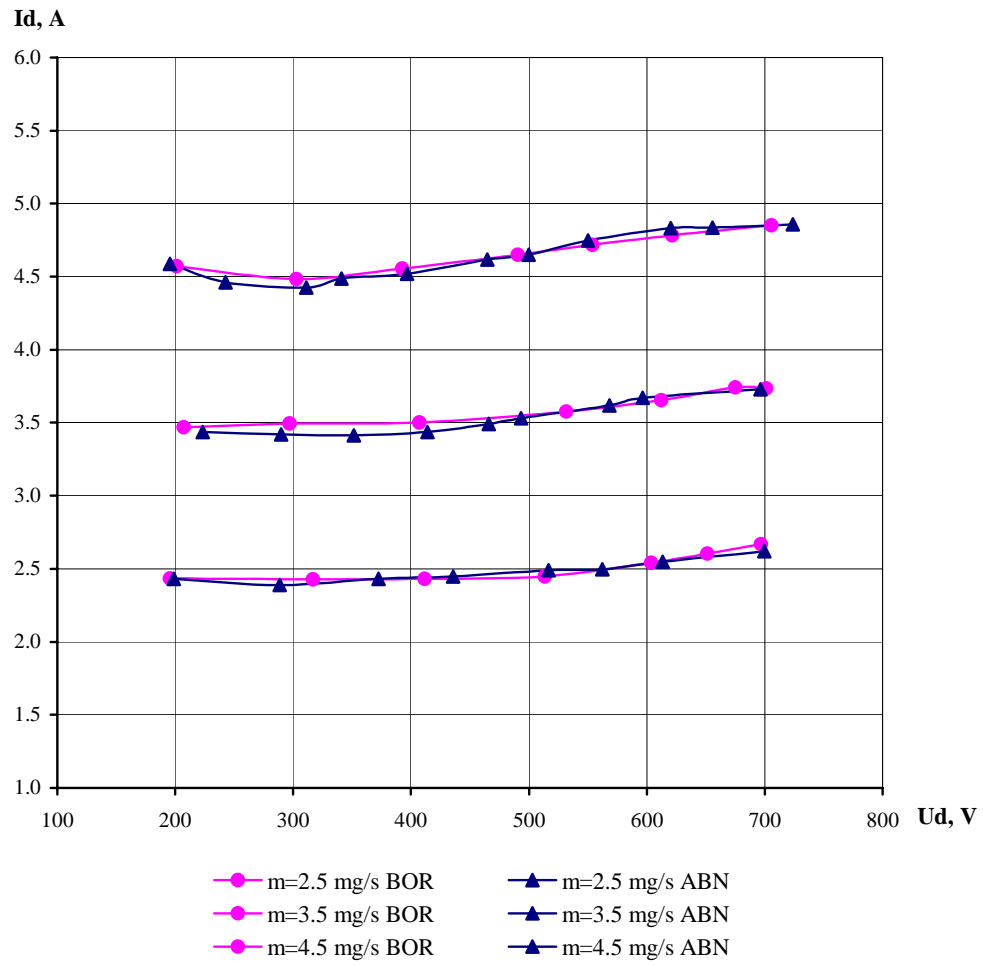


Fig. 2. Voltage-current characteristics the Hall Thruster model with replaceable rings made of borosil (BOR) and ALN-BN (ABN) ceramics.

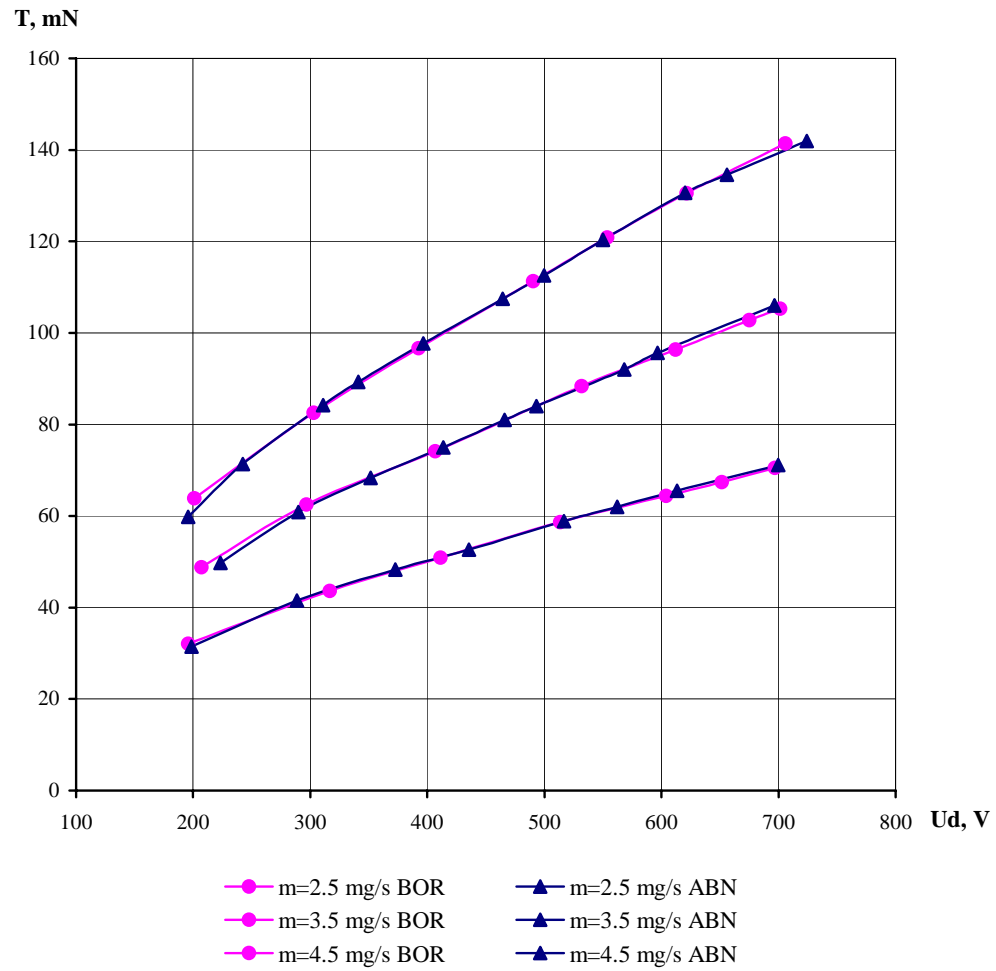


Fig. 3. Thrust versus discharge voltage.

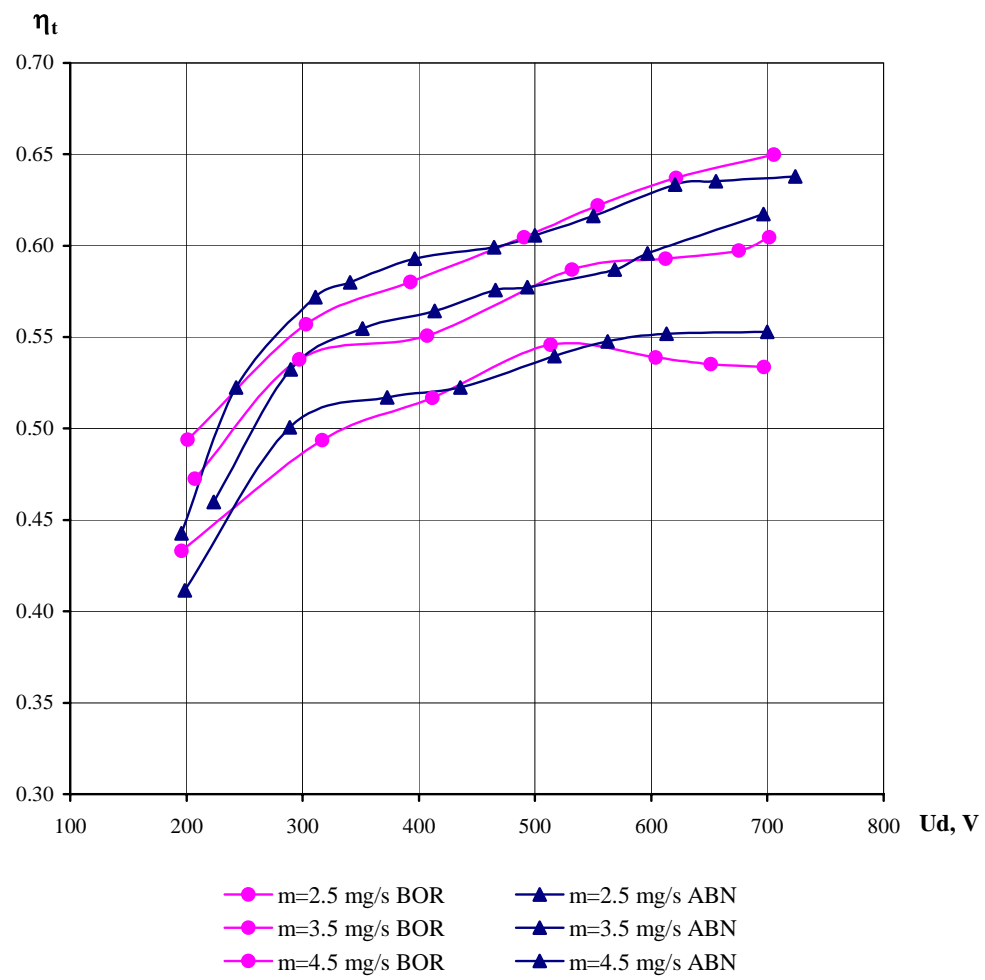


Fig. 4. Thrust efficiency versus discharge voltage.

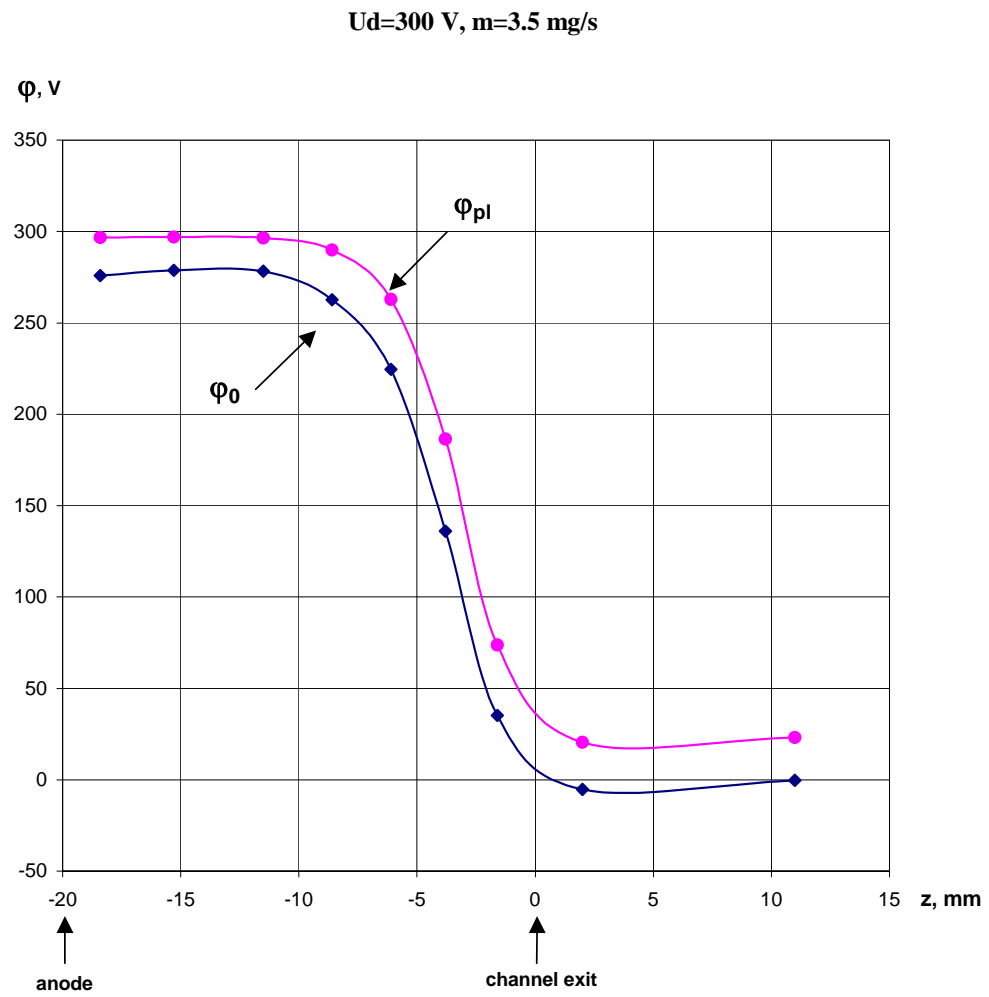


Fig. 5. Probe floating (ϕ_0) and plasma (ϕ_{pl}) potential distributions along the accelerating channel obtained with replaceable ring made of borosil.

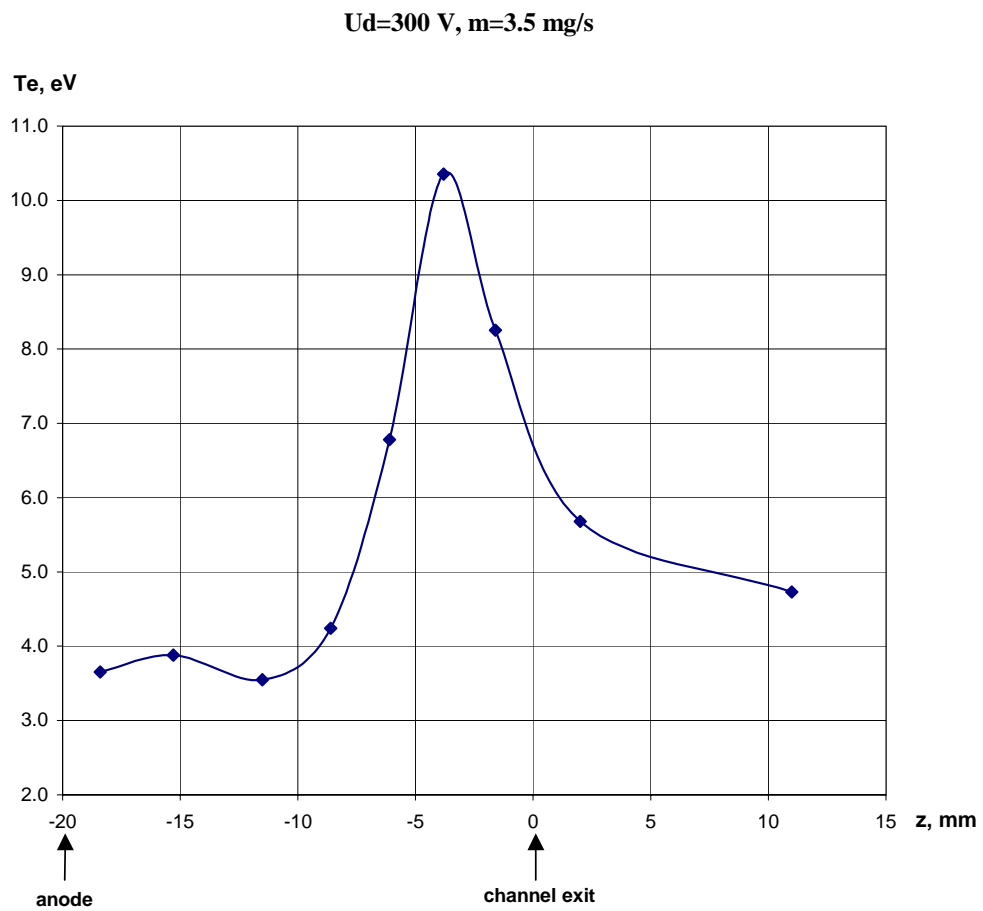


Fig. 6. Electron temperature distribution along accelerating channel obtained with replaceable ring made of borosil.

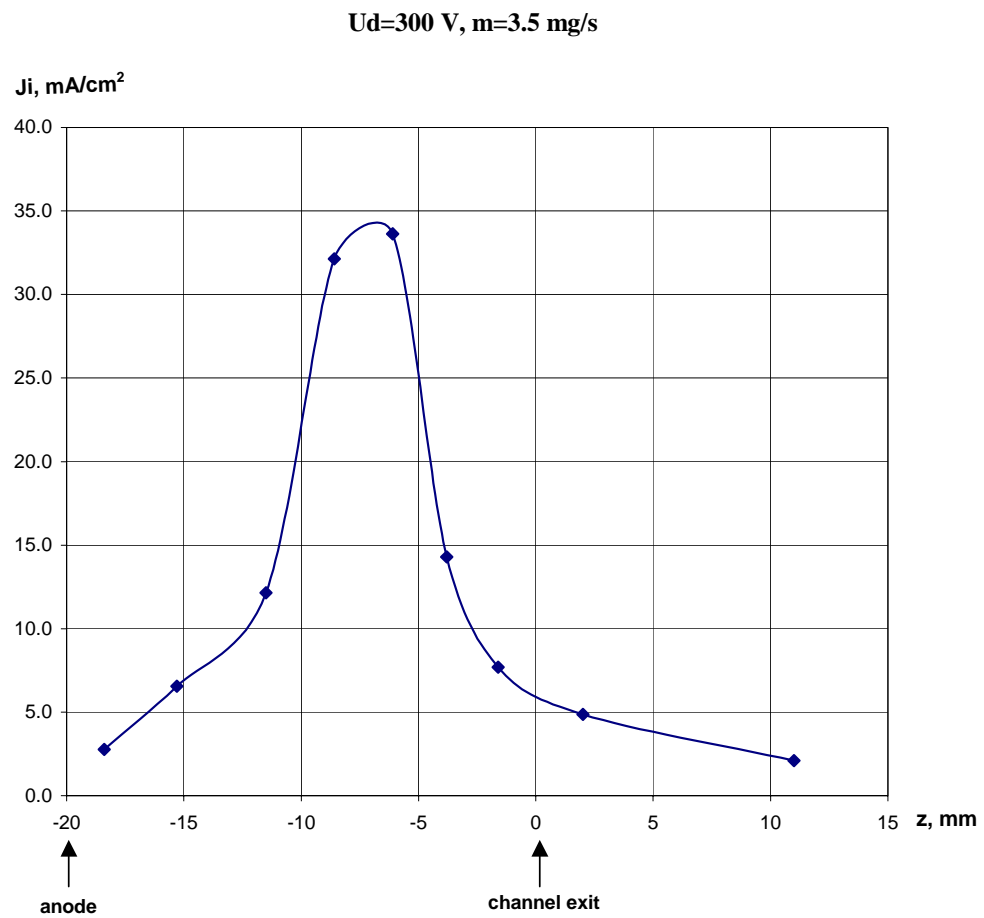


Fig. 7. Ion current density distribution along the accelerating channel obtained with replaceable ring made of borosil.

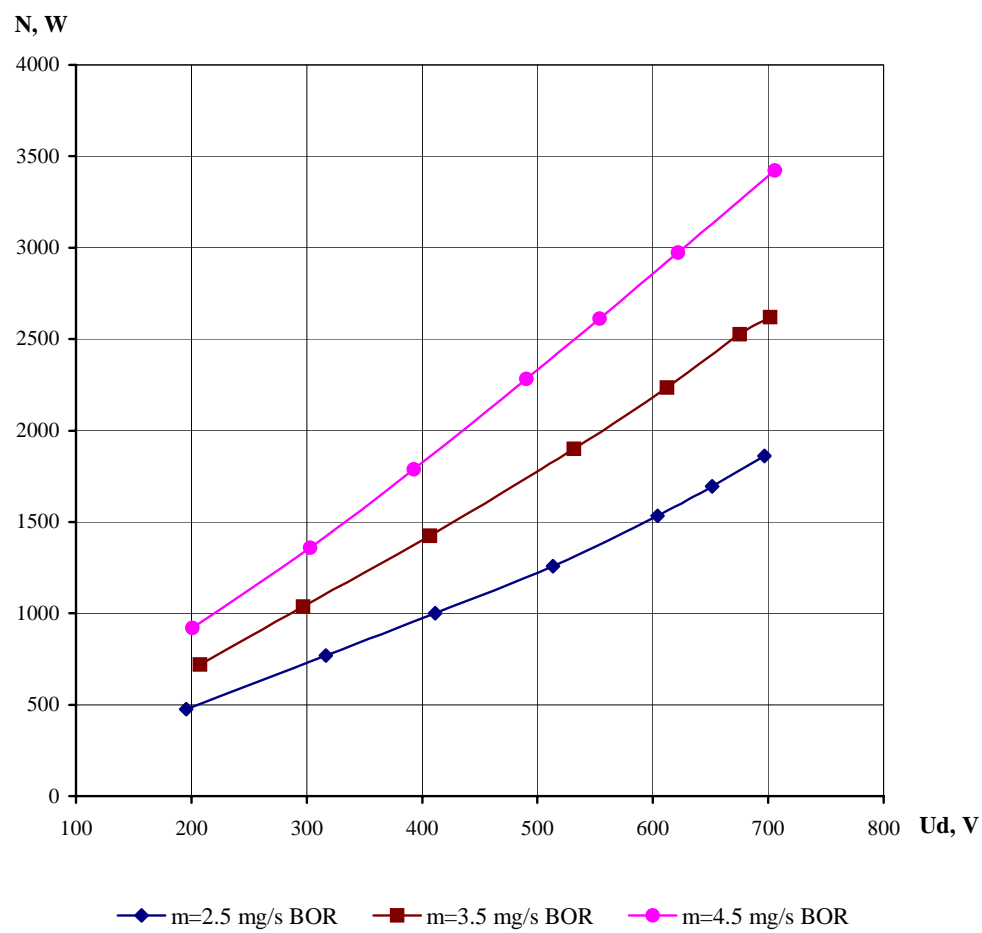


Fig. 8. Discharge power versus discharge voltage.

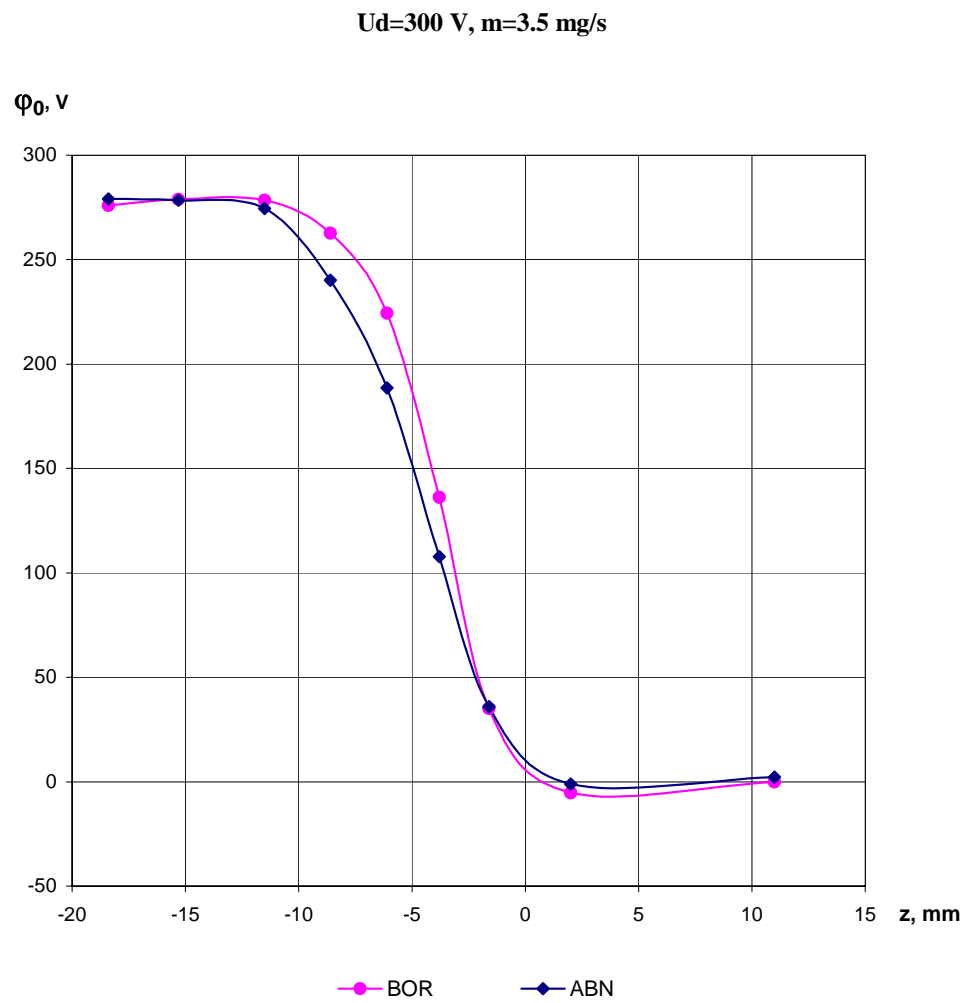


Fig.9. Distributions of the probe floating potential along external wall of the thruster model discharge chamber with borosil (BOR) and AlN-BN (ABN) rings.

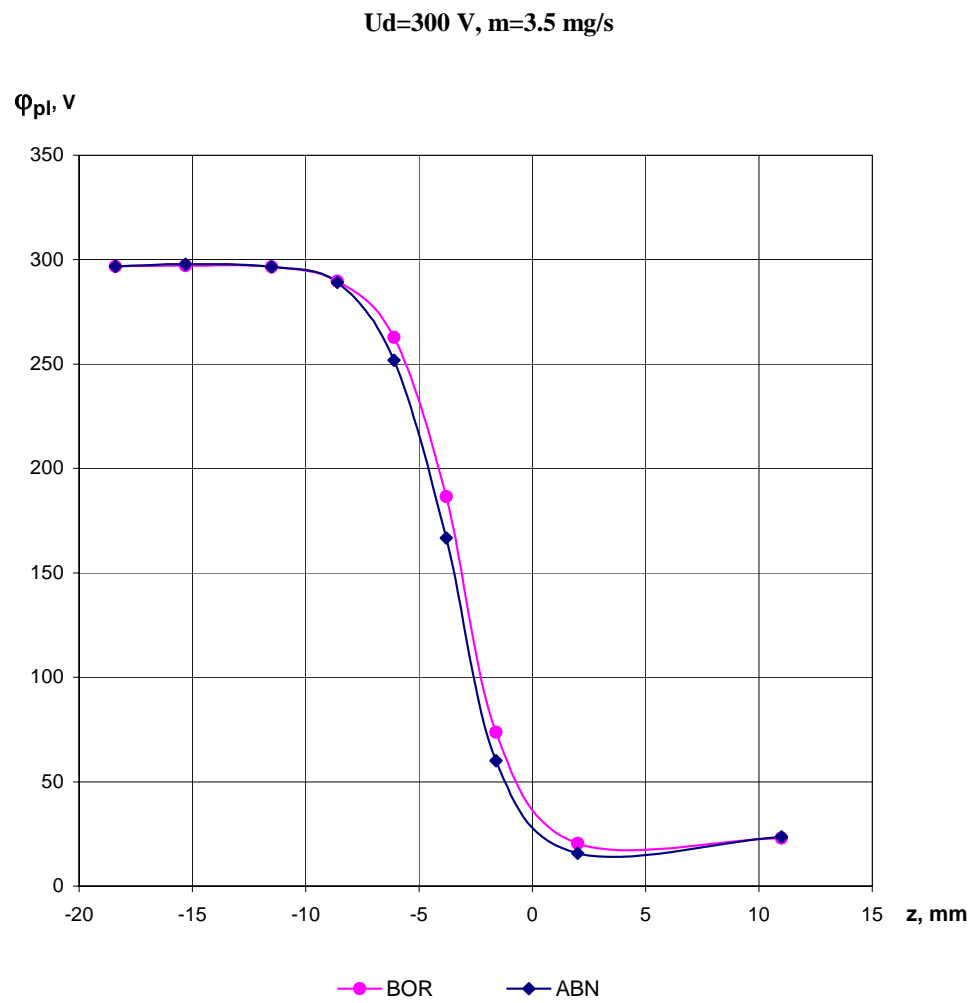


Fig.10. Plasma potential distributions along external wall of the thruster model discharge chamber with borosil (BOR) and AlN-BN (ABN) rings.

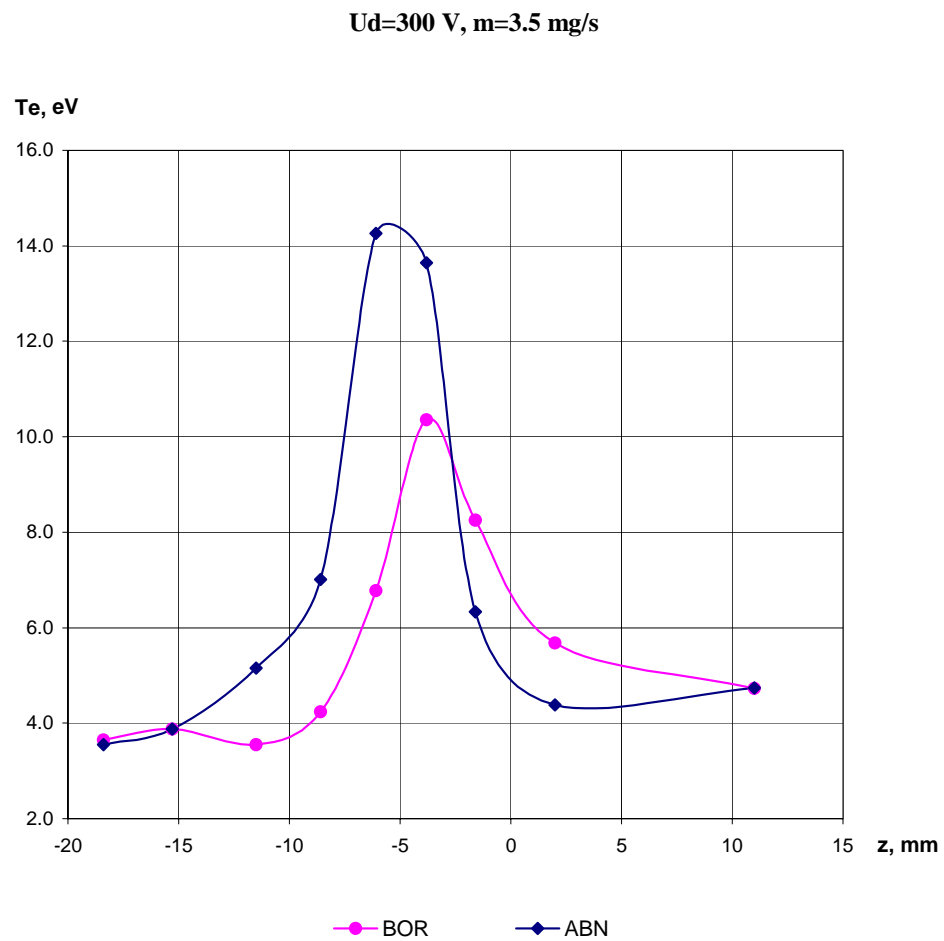


Fig.11. Electron temperature distributions along external wall of the thruster model discharge chamber with borosil (BOR) and AlN-BN (ABN) rings.

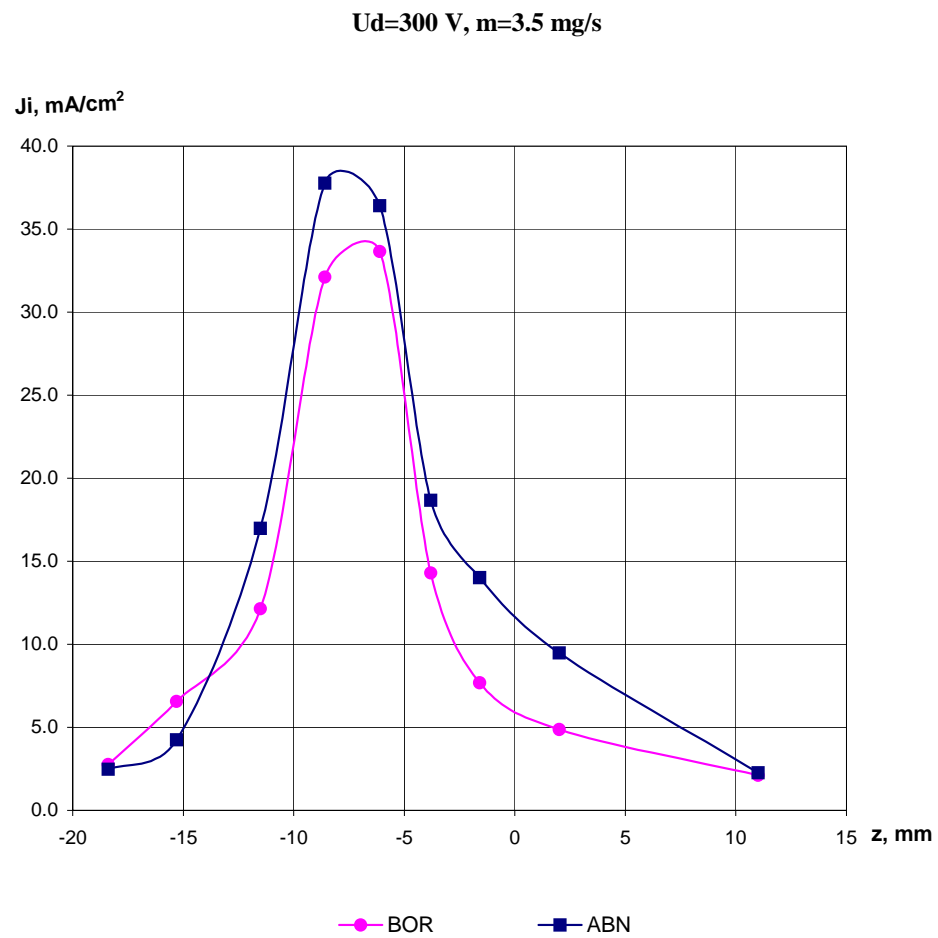


Fig.12. Probe ion current distributions along external wall of the thruster model discharge chamber with borosil (BOR) and AlN-BN (ABN) rings.

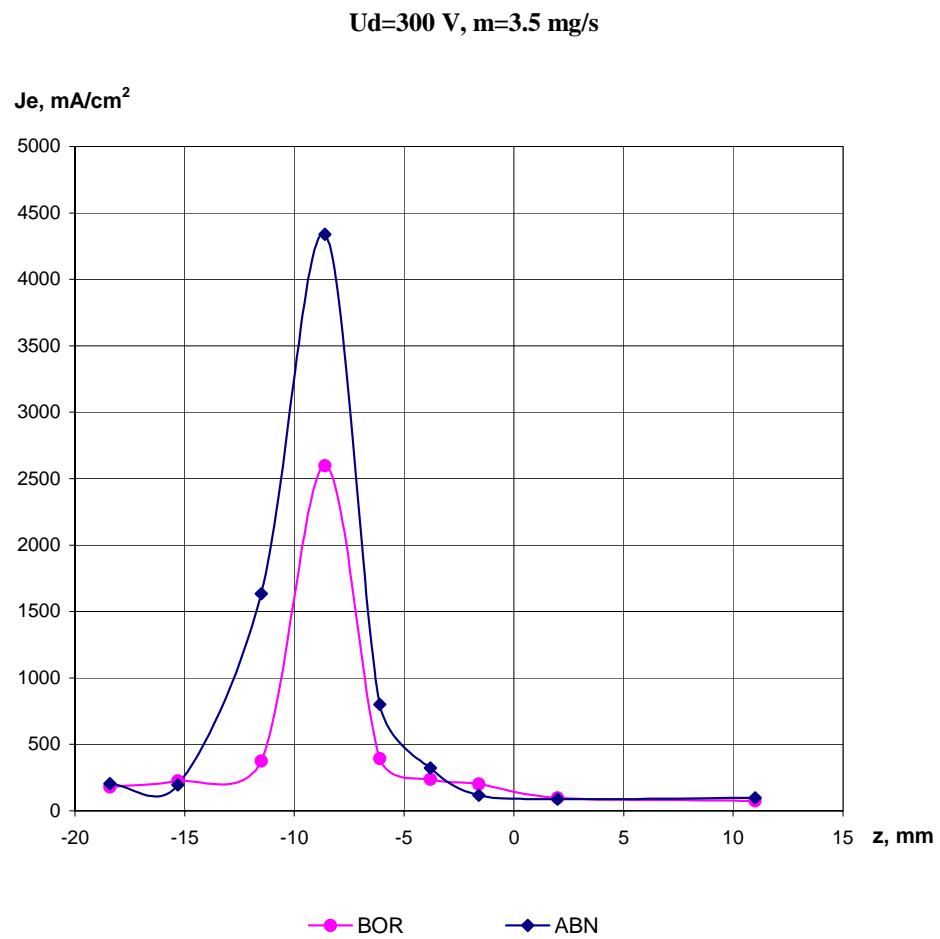


Fig.13. Probe electron current distributions along the external wall of the thruster model discharge chamber with borosil (BOR) and AlN-BN (ABN) rings.

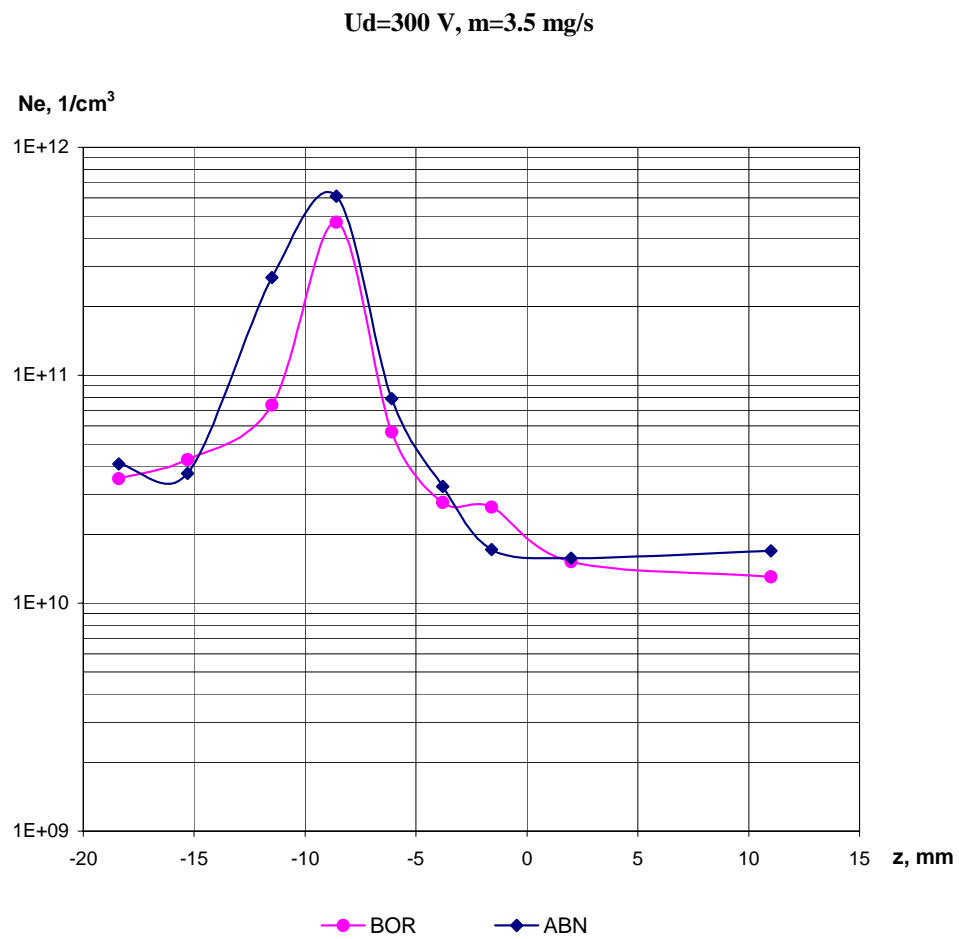


Fig.14. Electron (plasma) concentration distributions along external wall of the thruster model discharge chamber with borosil (BOR) and AlN-BN (ABN) rings.

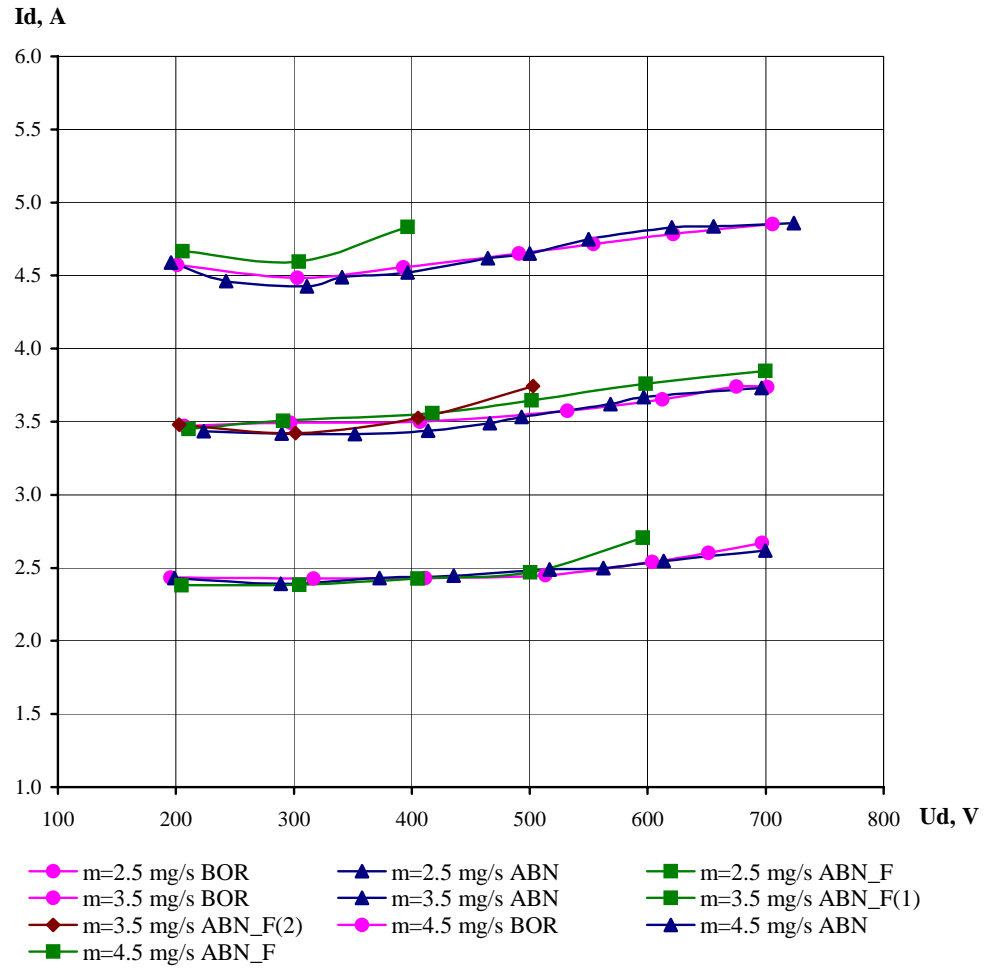


Fig. 15. Voltage-current characteristics of thruster model with rings made of different ceramics.

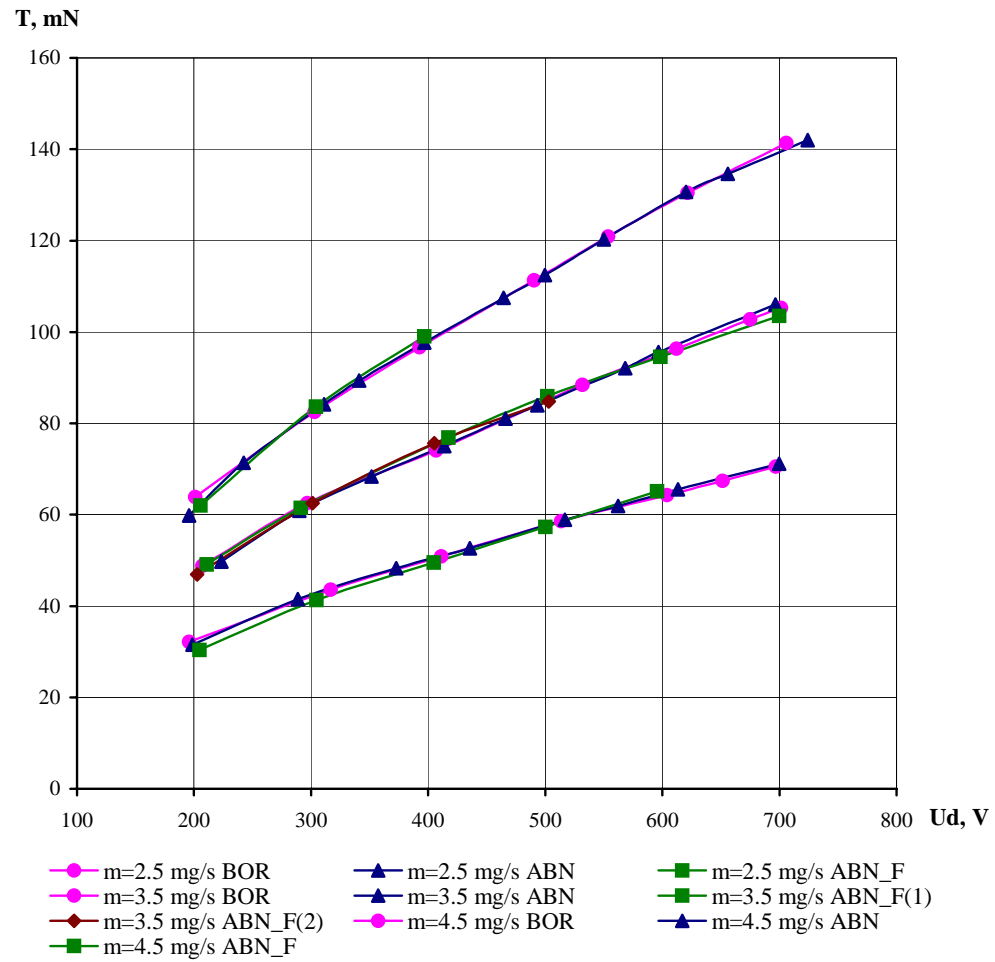


Fig. 16. Thrust versus discharge voltage.

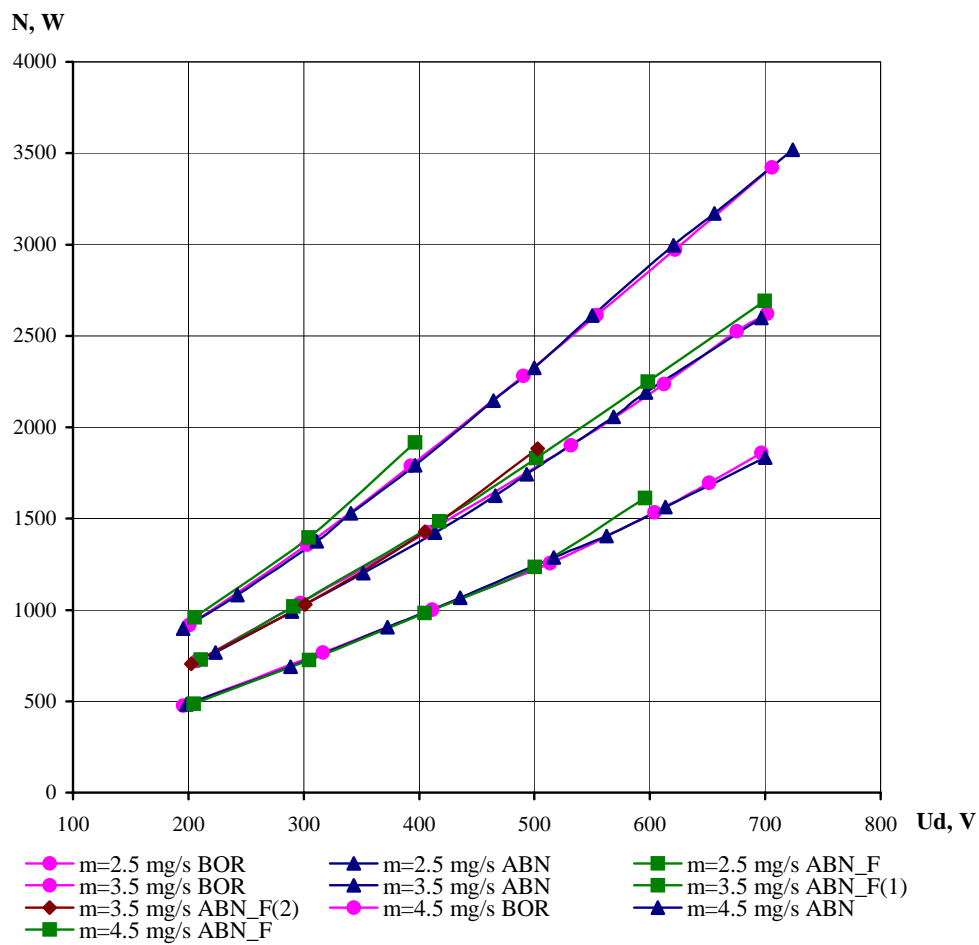


Fig. 17. Discharge power versus discharge voltage.

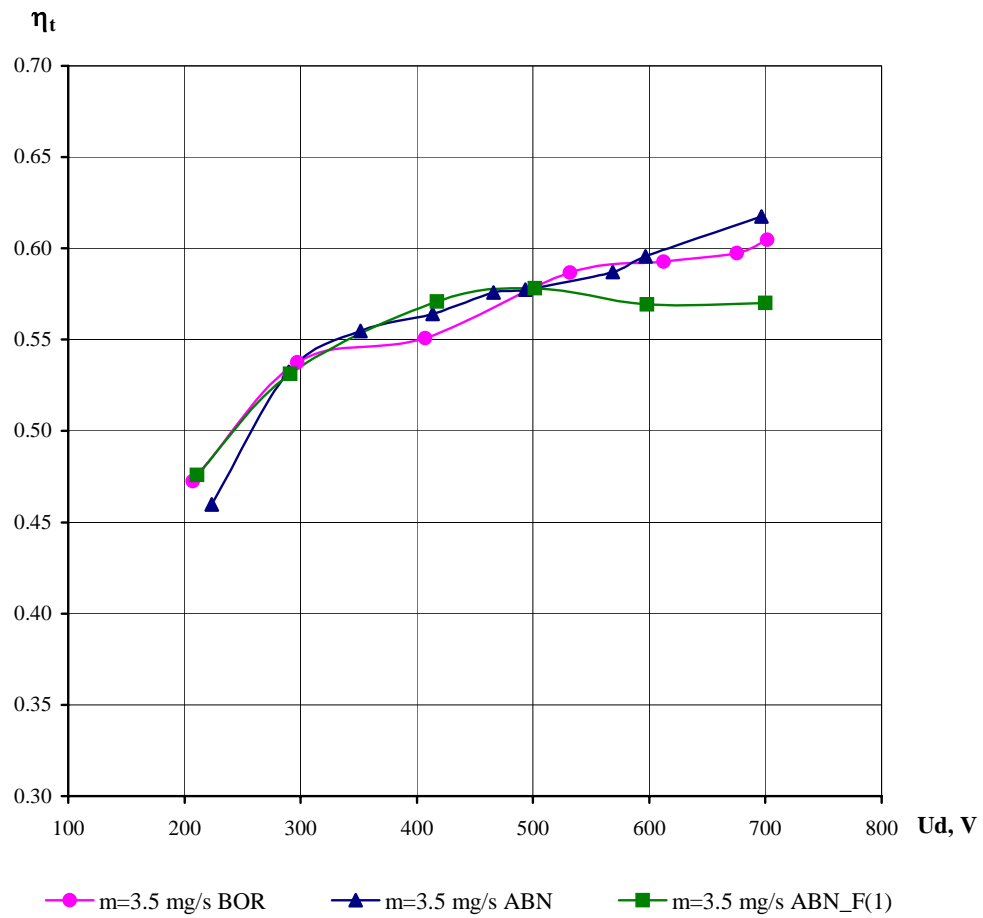


Fig. 18. Thrust efficiency versus discharge voltage.

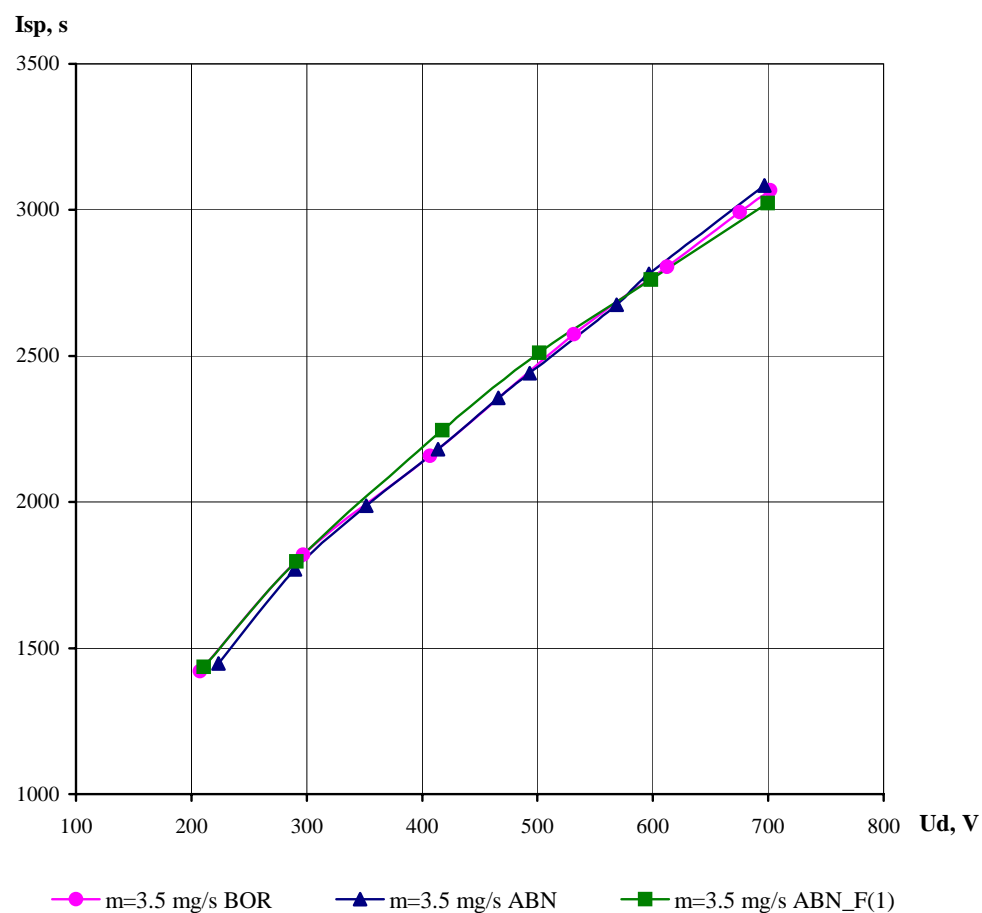


Fig. 19. Specific impulse versus discharge voltage.

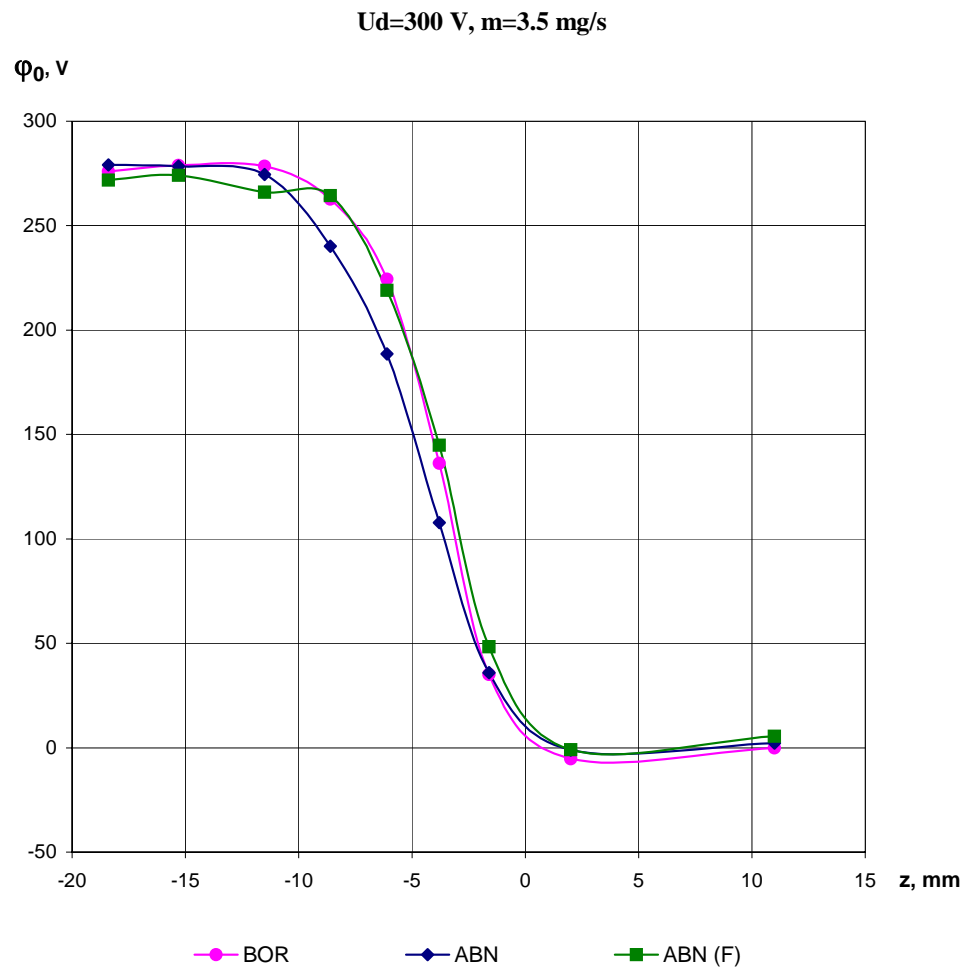


Fig. 20. Probe floating potential along the accelerating channel.

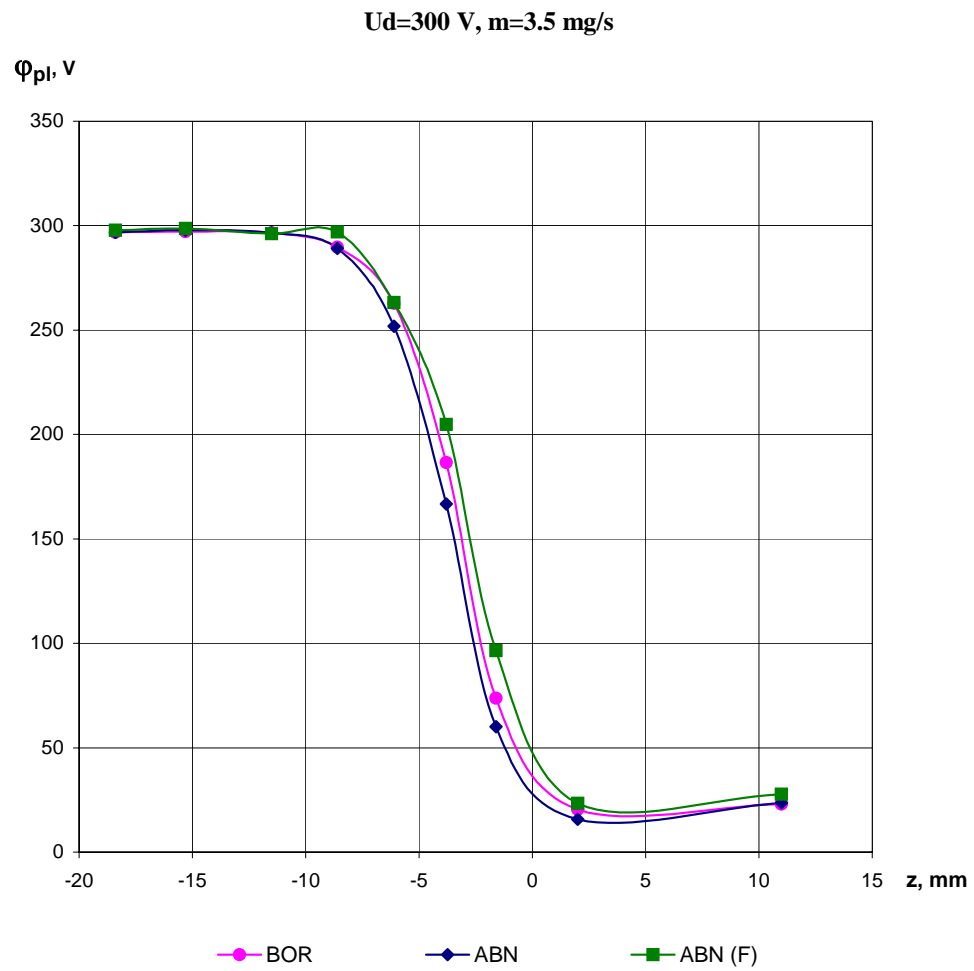


Fig. 21. Plasma potential along the accelerating channel

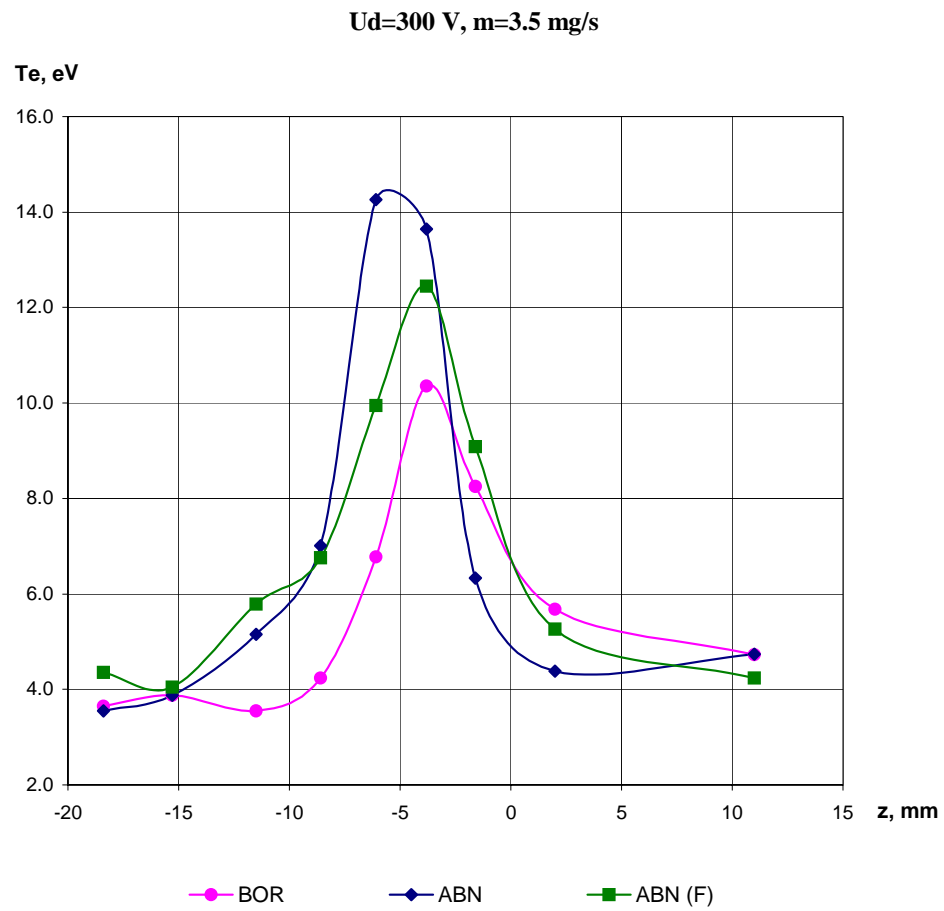


Fig. 22. Electron temperature distribution along the accelerating channel.

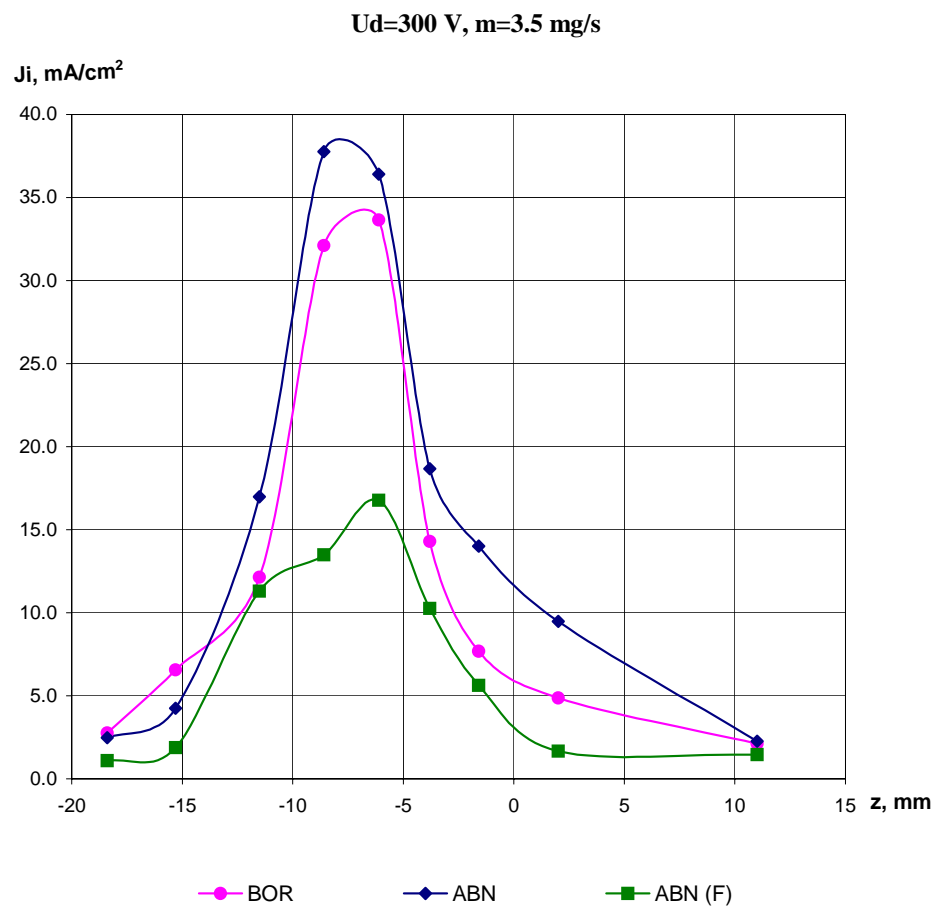


Fig. 23. Probe ion current distribution along the accelerating channel.

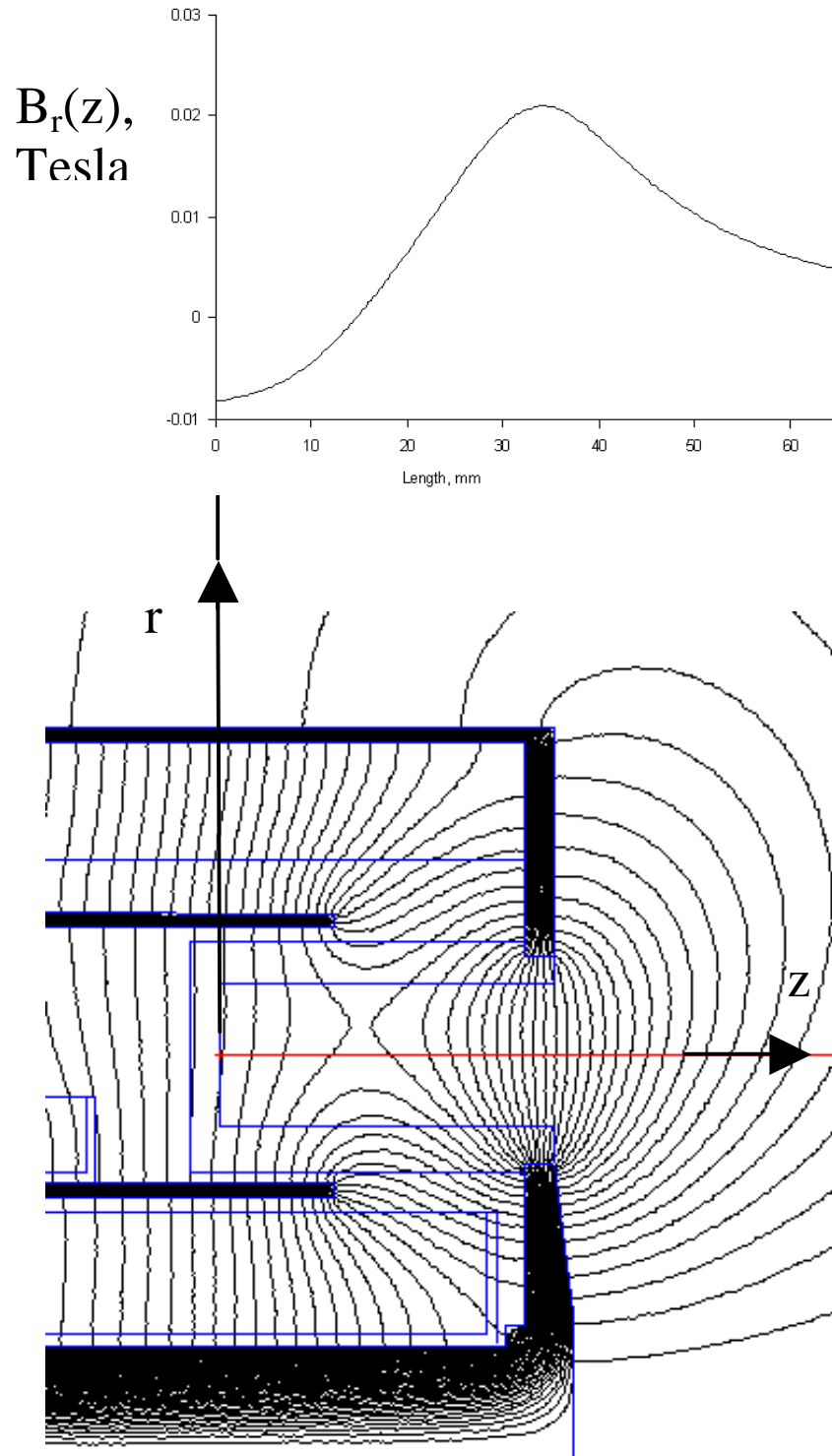


Fig. 24. Magnetic field topology and magnetic induction distributions along the accelerating channel mid surface for optimized operation mode with borosil ring ($I_{m1}=1.09\text{A}$, $I_{m2}=0.48\text{A}$, $I_{m3}=-2.5\text{A}$).

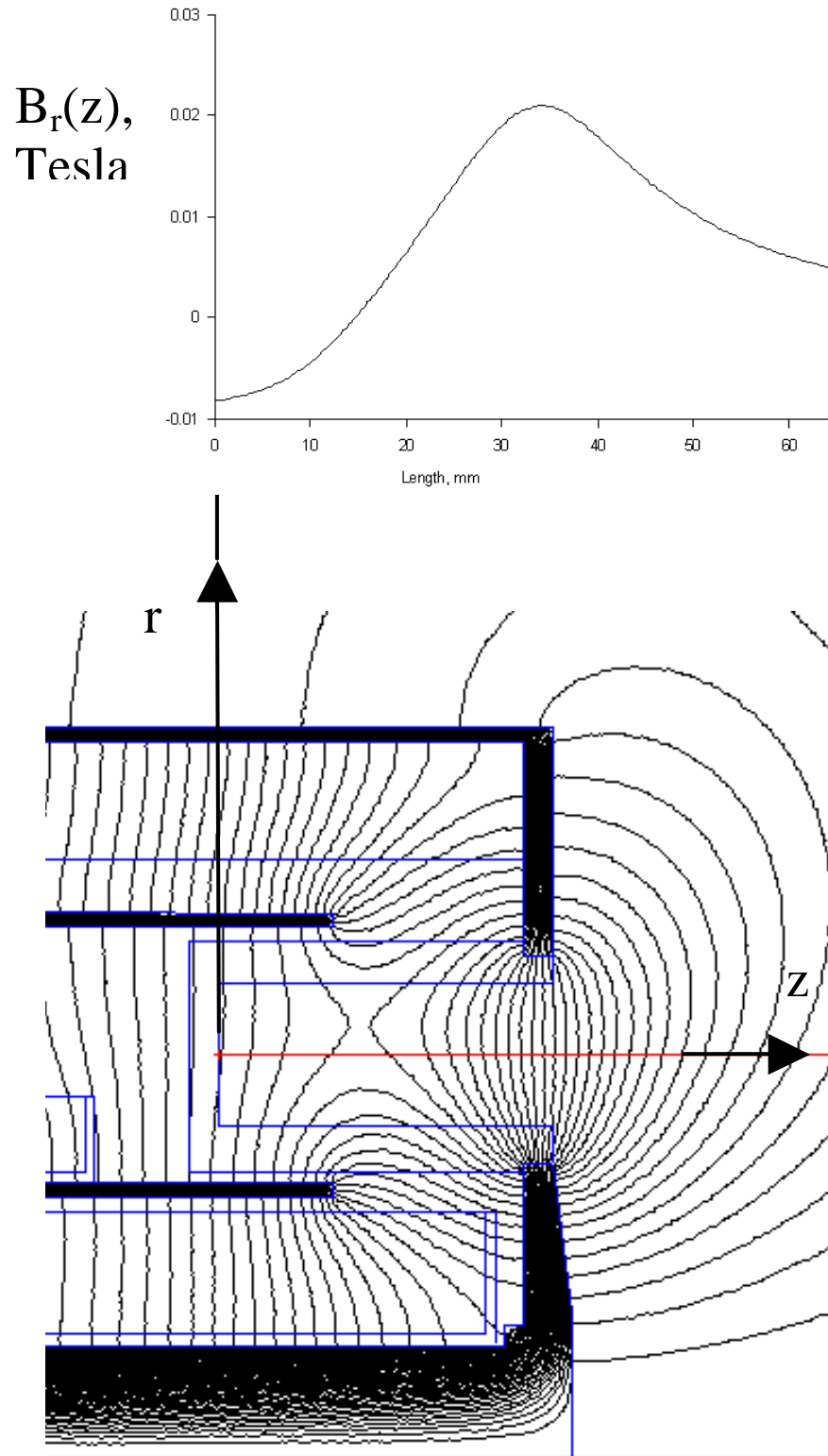


Fig 25 Magnetic field topology and magnetic induction distributions along the accelerating channel mid surface under optimized operation mode with ABN ring ($I_{m1}=1.21\text{A}$, $I_{m2}=0.49\text{A}$, $I_{m3}=-2.5\text{A}$).

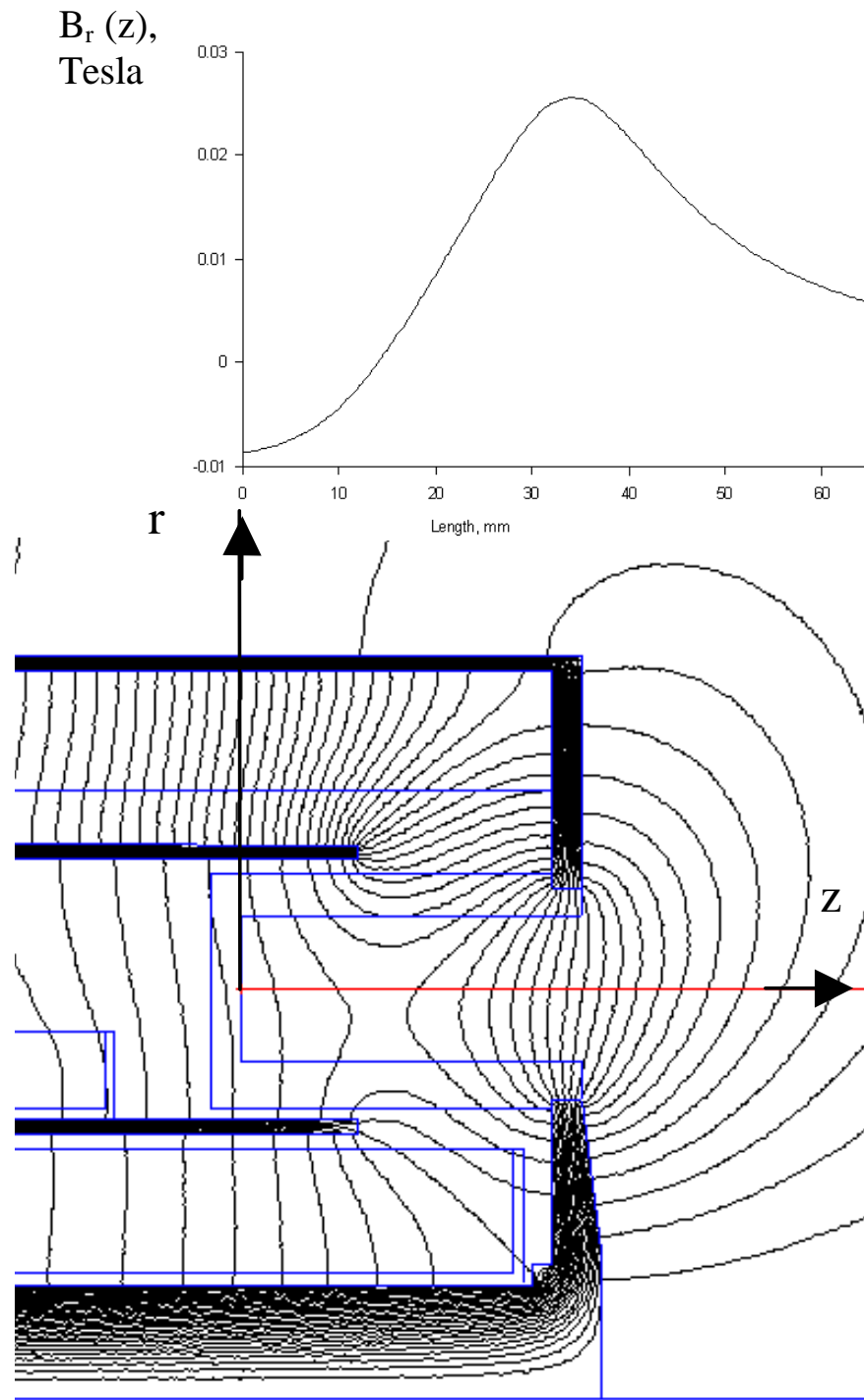


Fig.26. Magnetic field topology and magnetic induction distributions along the accelerating channel mid surface under optimized operation mode with ABN(F) ring ($I_{m1}=0.93\text{A}$, $I_{m2}=1.09\text{A}$, $I_{m3}=-2.58\text{A}$).